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SEATTLE, WASHINGTON

PROGRESS REPORT NO. 2

for

EXPERIMENTAL AND THEORETICAL INVESTIGATION OF WIND TUNNEL GEOMETRY, EMPHASIZING FACTORS PERTINENT TO V/STOL VEHICLES TESTING

at

N GR - 48 - 002 - 010

THE UNIVERSITY OF WASHINGTON

SEATTLE, WASHINGTON 98105

for

The Period from March 16, 1965 to September 15, 1965

under

NASA Grant NGR-48-002-010

by

R. G. Joppa
Principal Investigator
January 15, 1966

ABSTRACT

During the reporting period, March 15, 1965 to September 15, 1965, some progress was made on the experimental program and on the two parts of the analytical study of V/STOL testing problems.

The experimental program was begun with the installation of a powered rotor model in the wind tunnel. Force and moment data were taken at various longitudinal stations along the test section centerline in an effort to find the effects of testing near the ends of the section. The results were inconclusive and do not show the effects sought. A better system of measuring tunnel air speed is needed, and testing must be done at a higher advance ratio.

The analysis of tunnel internal flow by the use of the vortex ring method was extended and improved by distributing the vorticity from discrete rings to continuous sheets along the walls. There is still some mechanical difficulty with the computation of some parts of this, but it is believed that these problems are not serious. Much has been learned about the art of representing continuous distributions by singularities.

A beginning was made on the basic problem of calculating flow fields of highly loaded systems in free air. A survey of the literature was made and it was found that a simple representation of the vortex system was adequate to calculate the trajectory of a streamline. Of considerable interest to the calculation of interference is the demonstration that the vortex filaments trail downward at about one-fourth the angle of the mass of air as calculated by simple momentum theory.

In discussions with the grant monitor, it was decided to request extension of the grant to June 30, 1966 without additional funds.

EXPERIMENTAL

The experimental program to determine the length allowable in a two-test-section tunnel proceeded with the installation of a powered rotor model in the larger test section. A program of testing was begun to measure forces and pitching moments at several stations along the centerline and downstream to the beginning of the second contraction. Pressure data were taken on the walls and tufts on the walls were observed.

Analysis of the data was not revealing of any significant trends. Repeatability, while apparently good enough for normal testing, was sufficiently uncertain that the effects looked for were lost in the scattered data. Therefore, a detailed study was begun to search for sources of error.

In the design of the experiment it was thought that the effects of interest would be those occurring at large downwash angles, and so the test series was executed at low advance ratios and rather high disc loadings. This, of course, introduced several problems beyond those of tunnel flow direction. Among problems introduced are the uncertainty of flow separation from the tunnel top and flow re-circulation in the test section. An attempt was made to avoid these problems by staying at sufficiently high advance ratios, but the pressure and tuft data indicate that the region chosen was marginal.

Another problem was the measurement of tunnel airspeed. It had been expected that measurement of static pressures on the tunnel walls in the normal way would give adequate airspeed information, but the influence of the rotor appears to be felt more strongly than anticipated. Since the airspeeds are low with respect to rotor wake velocities, the interference of the rotor on pressure measurements can have a very large percentage affect on the airspeed value and, consequently, on lift coefficients and advance ratios. Data showed that increasing the power input to the rotor while the rotor was tilted forward required more tunnel propeller rpm to maintain the same speed indications. Therefore, it was decided that a completely independent airspeed measuring system would be required.

An exploration into other airspeed measurement means was made. An attempt was made to find a correlation between tunnel airspeed and tunnel propeller rpm with various amounts of thrust or drag produced by a model propeller installed in the test section. A rather good correlation which appeared to be workable was found when the tunnel airspeed was high, but the effects of thrust were quite large at low tunnel airspeed. Consequently, it was decided that an entirely independent airspeed measurement scheme would be necessary and that the test series would have to be run at higher advance ratios.

ANALYSIS OF THE INTERNAL FLOW FIELD

The analytical work in this area was extended. The formulation of the vortex ring method for calculating internal flows as stated in Reference (1) was checked in detail. The location of control points had previously been explored and found to be of considerable importance. In the process of reviewing the previous work, an error in the calculation of the control point location was found. It had been shown that the control points should be located not on the centerline, but about six-tenths of the distance laterally from the centerline to the wall of the tunnel. The computer program, however, had been set up to calculate a dimension that was six-tenths of the ordinate of the nearest upstream vortex ring. Correction of this error changed the magnitude of the flow and gave better agreement with the area ratios.

It was found that the total flow velocity is extremely sensitive to the details of the exit. As in thin airfoil theory, the Kutta condition at the trailing edge is a most powerful influence on the flow and must be very carefully handled. Attempts to end the expansion section at the correct area, but with an expanding angle, led to much too high speed internal flow. Attempts were made with straight exit sections of varying length with improvement. A final configuration was chosen in which the entry and exit lengths were each about one diameter. The resulting centerline velocities, with these changes, were in agreement with the area ratios and the magnitudes were in agreement with the desired condition of uniform inlet and exit flow.

An investigation was made into non-uniform vortex spacing with very poor results. Closer spacing (doubled) in the smallest section led to a velocity distribution along the centerline which was more nearly uniform, but also resulted in inducing additional flow into that region of the tunnel in violation of continuity. It appears that the vortex strengths are biased when the control points and vortex rings are not uniformly spaced.

Some considerable effort was expended in calculating the flow fields off the centerline of the tunnel. It was realized from the first that the quality of solution would deteriorate at points near the wall, depending on whether those points were taken near a vortex ring or a control point. Profiles in these two stations were compared and found to agree well in the central two-thirds of the larger test section and in the central one-half of the smaller. Although this is probably sufficient for wind tunnel design, more confidence in the results would be felt if the wall could be approached more closely. The plan for this was to distribute the vorticity determined by the discrete ring method in some way to permit calculation of internal velocities all the way to the wall.

Several methods of distribution were considered, including step-wise distribution, a series of continuous straight lines, and a power series. Since the solutions already obtained were nearly good enough, it was decided that the step-wise distribution offered an adequate improvement at the minimum increase in complexity.

Considerable difficulty was encountered with this approach. Integrating the effect of the distributed vorticity on the flat uniform sections gave no trouble, but the tapered sections introduced complications. The analytical integrals contained a number of special cases where ambiguity of signs could not be resolved. Another form of the integral was eventually found in which the signs were determinable, but at the end of the reporting period there was still trouble in running the computation. In an interim effort to see if the computation had improved by the distribution of vorticity, the sloping sections were replaced by a series of flat, straight, stair-step-like sections. Complete computations using this method gave what appeared to be excellent results in the stream-wise direction even close to the wall. The cross-flow components calculated by this method appeared inconsistent near the wall of the tunnel, so these were calculated using the singularity solution originally developed. This gave results which looked better, probably because the singularity values were determined by the cross-flow condition at the wall in the first place. Flow fields were calculated this way for the geometry of the UWAL* one-eighth scale model tunnel and for another two-test section tunnel having a short test section and rather sharp contractions. These figures are attached.

At this point, the general solution is incomplete due to the problems in calculating the effects of step-wise distributed vorticity. The difficulties are believed to be mechanical in nature and not basic to the nature of the problem.

INTERFERENCE CALCULATIONS

The initial objective in this effort was to explore the aerodynamics of high-lift systems in free air and in wind tunnels in order to find the difference to be charged to interference. The first system to be studied was a simple, non-powered system in which the lift is generated by circulation. When circulation lift is large the usual linear approximations are no longer valid and so developments must be carefully done to avoid approximations. The work of Betz, Prantdl, Westberger, Kaden, and Spreiter and Sacks was reviewed and several theorems of vortex flow were checked. The approach of Cone was followed to solve for the trajectory of the wing wake. A set of conclusions has been reached which may illuminate the interference problem.

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The theorems state that the center of gravity of a vortex sheet remains at the same span-wise location after rolling up into a rotational core having the properties of a single filament. Furthermore, it has been shown that the rolling up distance is very short, being of the order of one-quarter the span for highly loaded low aspect ratio wings. Thus, the use of a simple, horseshoe vortex system is acceptable for calculating trajectories.

When the path followed by a trailing tip vortex is calculated, it is seen to move only under the influence of the other half of the pair and of the bound segment. It is easily seen that the trailing filament moves downward only one-fourth as fast as a streamline in the plane of symmetry, since the effect at the centerline is due to both trailing components at a distance of only one-half the span. The use of simple momentum theory yields a wake deflection very close to that calculated at the centerline due to the trailing pair. While simple momentum might be used to calculate the trajectory of the mass of air deflected, it will overestimate the final deflection of the vortex filaments by a little more than a factor of four. In some applications where the trajectories have been of interest only in the near neighborhood, the local downwash angle has been taken as one-half of the final angle found by the momentum theory, which reduces the error by one-half. An interesting result is that the effect of the bound segment causes the trailing filaments to move downward at very nearly their final angle right from the start.

CURRENT STATUS AND PLANS

The end of the reporting period corresponded to the beginning of the academic year. Two graduate students had been recruited during the spring term and were available to start work for the 1965-66 school year. Consultation with the grant monitor had resulted in a decision to request extension of the grant period to June 30, 1966 without additional funds, and this request is pending.

In the next period, it is planned that the revised test program will be carried out in the model tunnel with an independent airspeed system. The internal flow calculation program should be completed and a technical report prepared on that subject. Computation of vortex trajectories in a closed tunnel will be attempted by an extension of the internal flow calculation method combined with the free air vortex trajectory calculation method.

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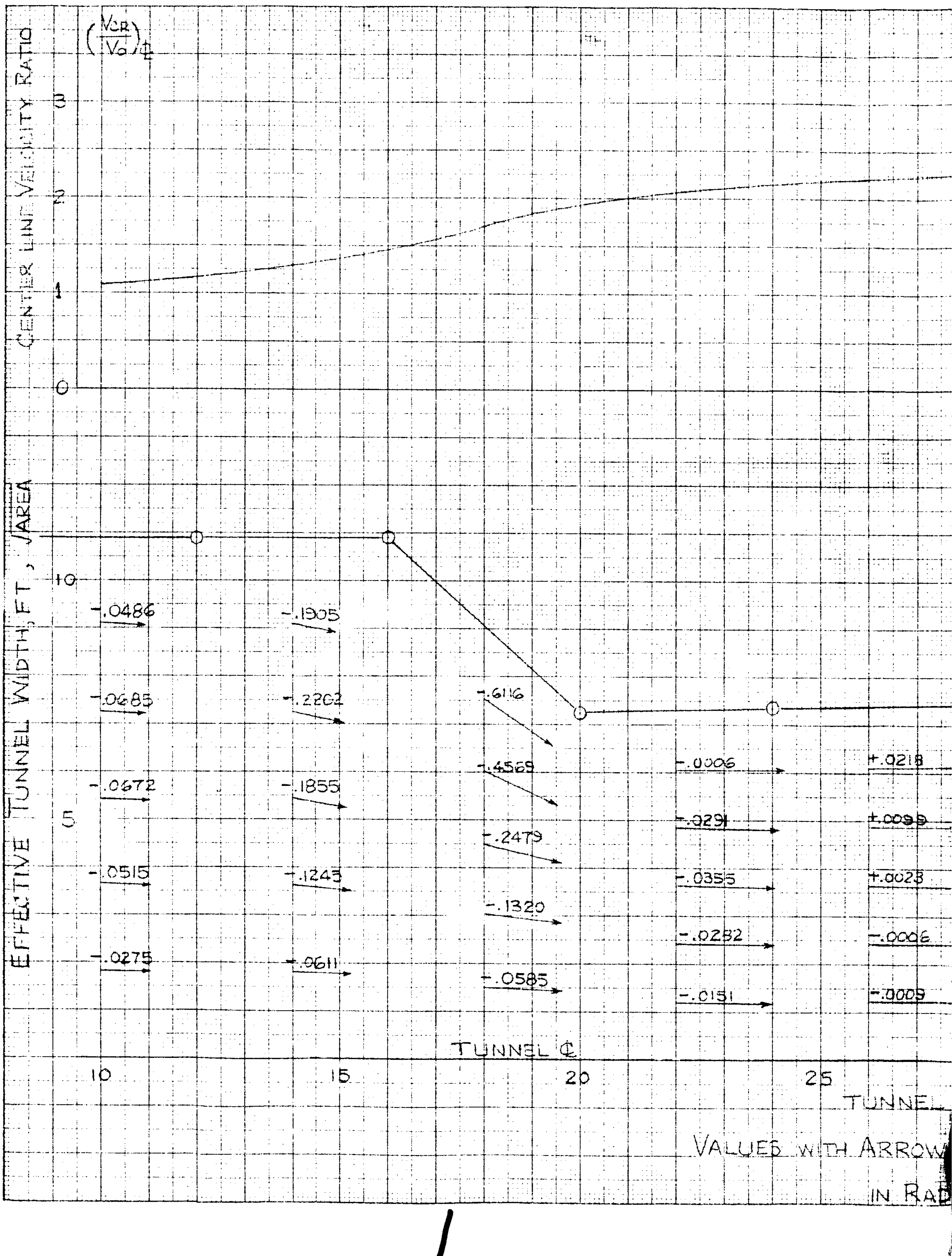
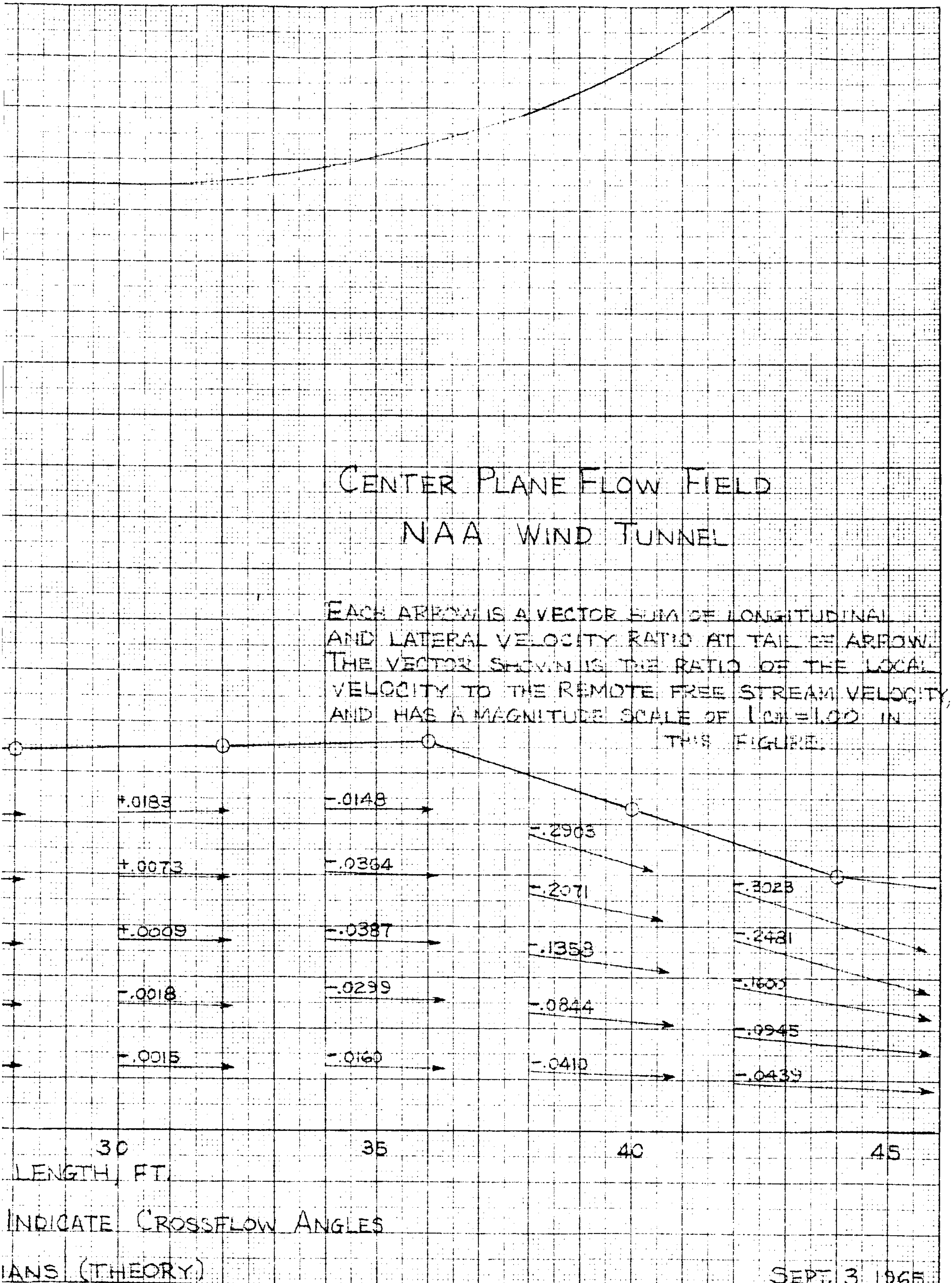

$\left(\frac{V_{CR}}{V_o}\right)_{℄}$
CENTER LINE VELOCITY RATIO
3
2
1
0
EFFECTIVE TUNNEL WIDTH, FT, JAREA
10
5
-.0486
-.1905
-.0685
-.2262
-.6116
-.0672
-.1855
-.4569
-.0006
+.0218
-.0291
+.0099
-.2479
-.0515
-.1245
-.0355
+.0028
-.1320
-.0282
-.0006
-.0275
-.0611
-.0585
-.0151
-.0009
TUNNEL ℄
10
15
20
25
TUNNEL
VALUES WITH ARROW
IN RAD


CENTER PLANE FLOW FIELD
NAA WIND TUNNEL
EACH ARROW IS A VECTOR SUM OF LONGITUDINAL AND LATERAL VELOCITY RATIO AT TAIL OF ARROW. THE VECTOR SHOWN IS THE RATIO OF THE LOCAL VELOCITY TO THE REMOTE FREE STREAM VELOCITY, AND HAS A MAGNITUDE SCALE OF 1 cm = 1.00 IN THIS FIGURE.
+.0183
+.0073
+.0009
-.0018
-.0015
-.0148
-.0364
-.0387
-.0299
-.0160
-.2903
-.2071
-.1353
-.0844
-.0410
-.3028
-.2481
-.1655
-.0945
-.0439
30
35
40
45
LENGTH, FT.
INDICATE CROSSFLOW ANGLES
IANS (THEORY)
SEPT. 3, 1965

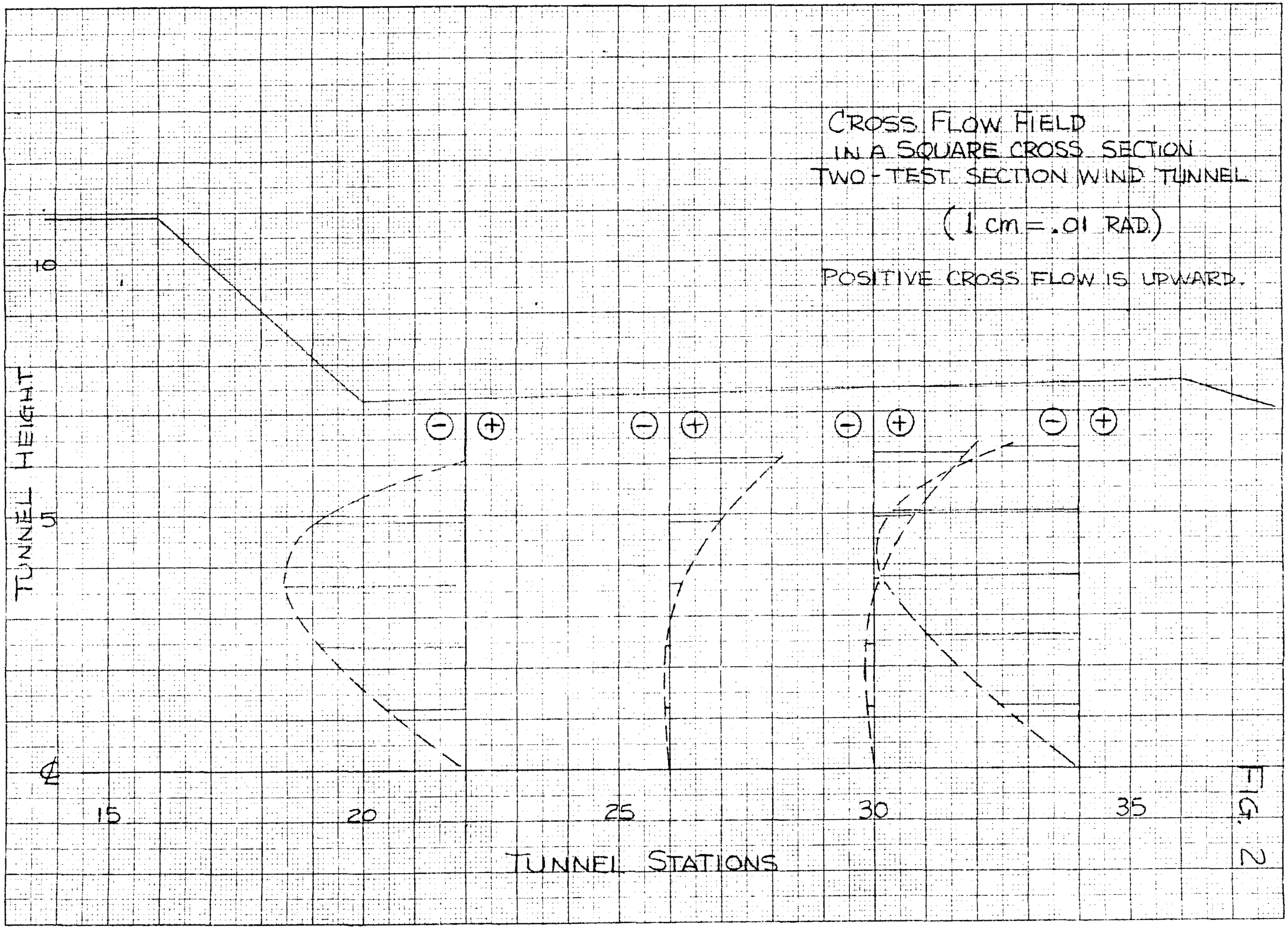
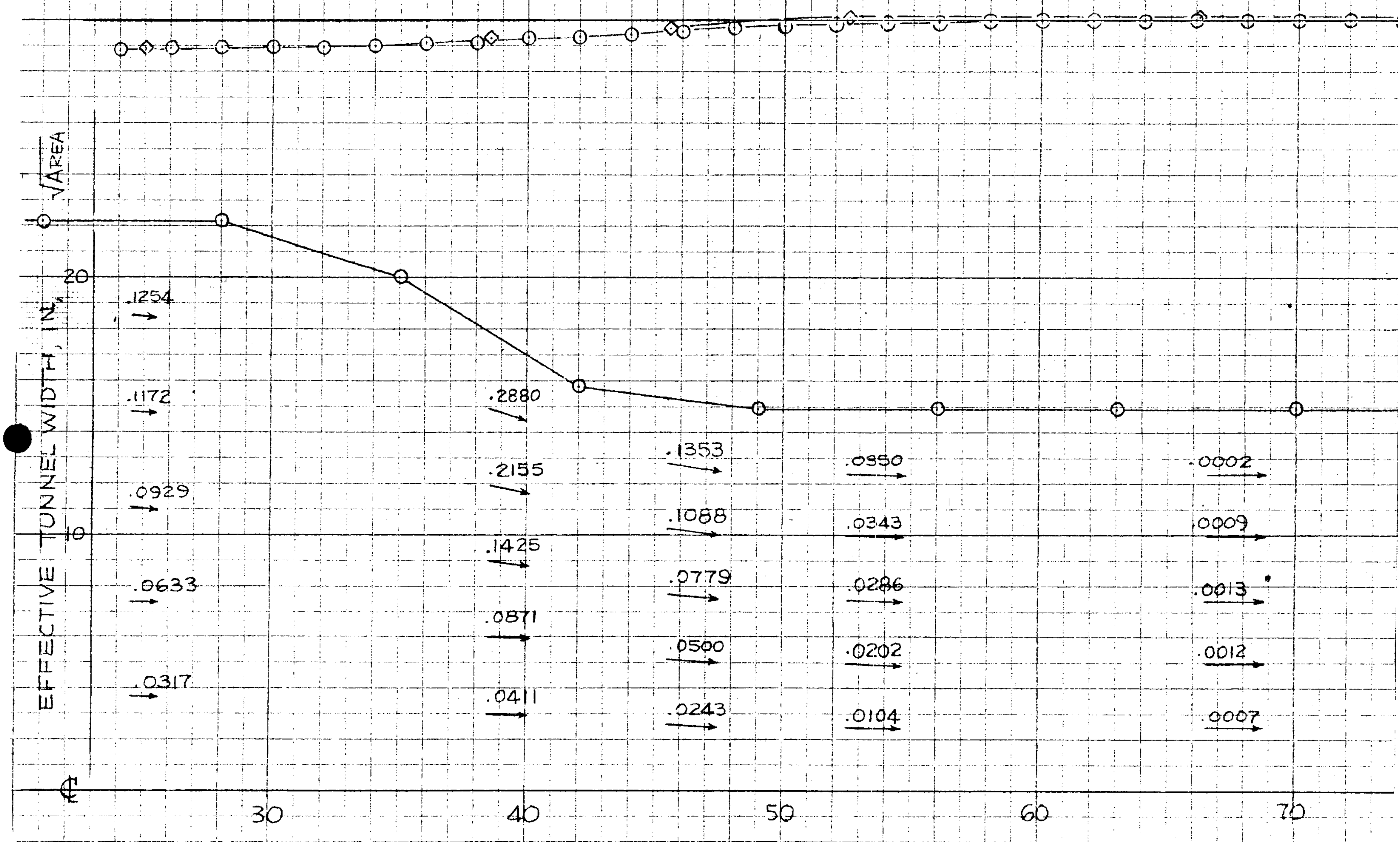

CROSS FLOW FIELD
IN A SQUARE CROSS SECTION
TWO-TEST SECTION WIND TUNNEL
(1 cm = .01 RAD.)
POSITIVE CROSS FLOW IS UPWARD.
TUNNEL HEIGHT
10
5
℄
15
20
25
30
35
TUNNEL STATIONS
−
+

FIG. 2


√AREA
EFFECTIVE TUNNEL WIDTH, IN.
20
10
℄
30
40
50
60
70
.1254
.1172
.0929
.0633
.0317
.2880
.2155
.1425
.0871
.0411
.1353
.1088
.0779
.0500
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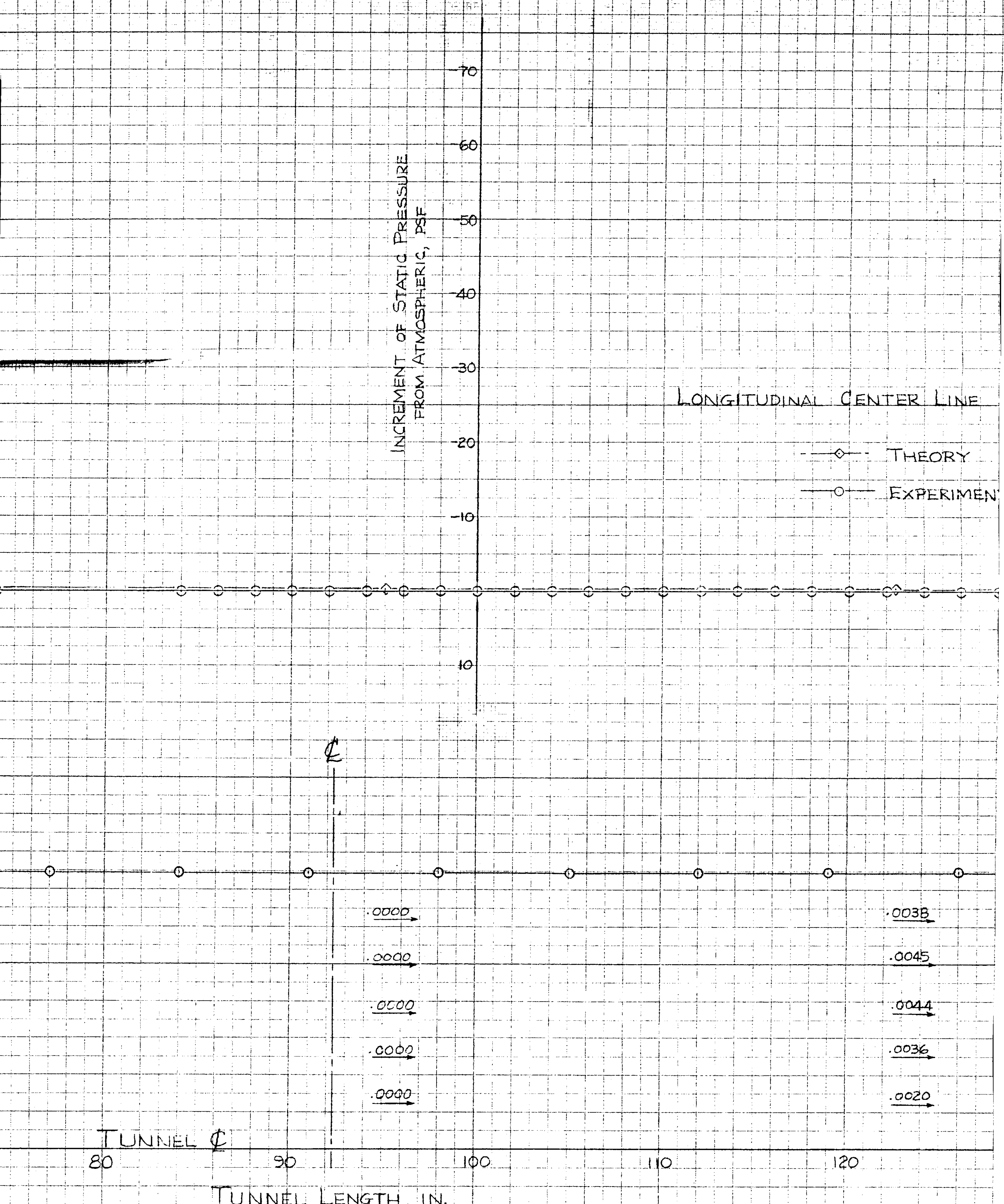
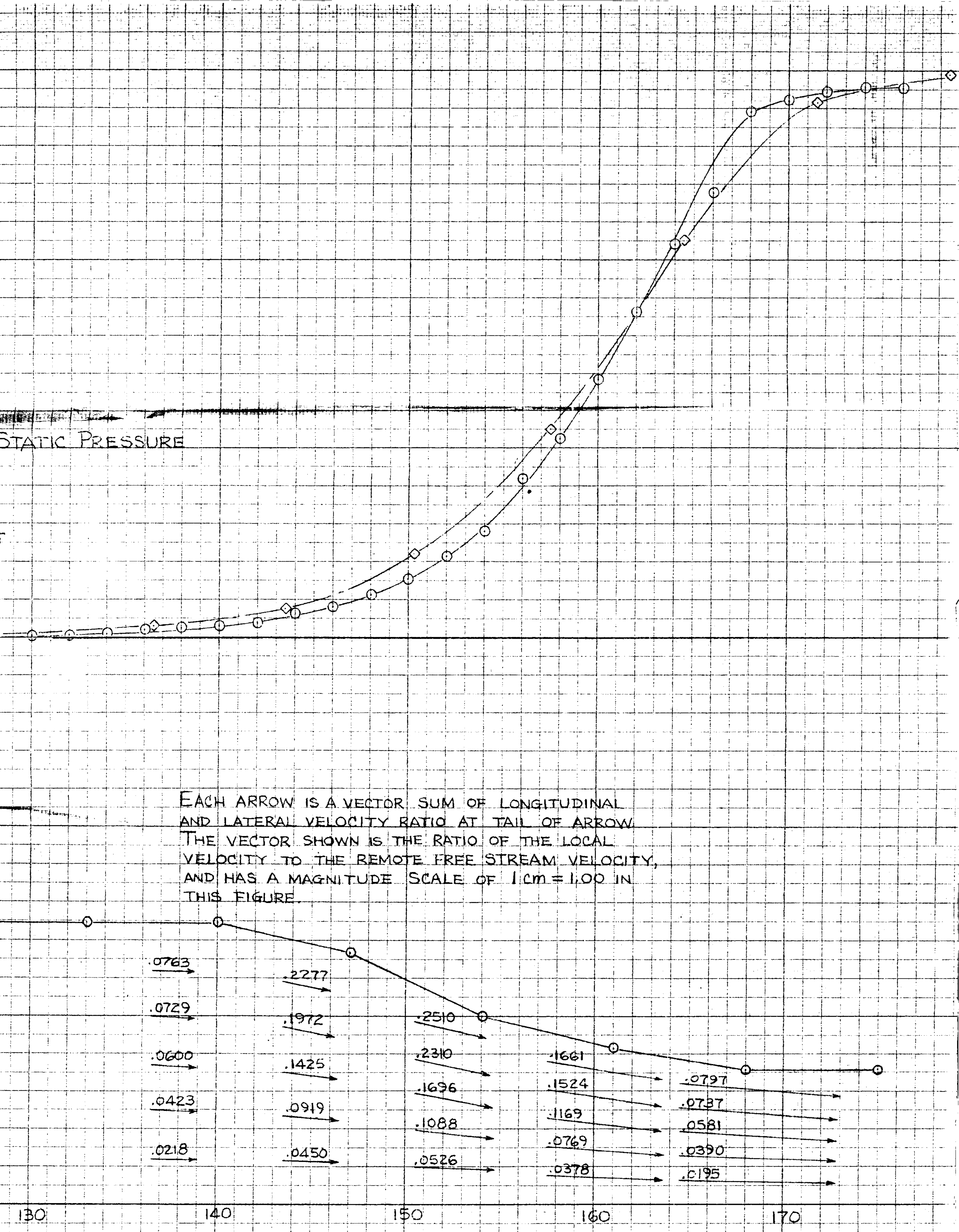
.0013
.0012
.0007

#1



VALUES WITH ARROW INDICATE CROSSFLOW ANGLES IN RADIANS (THEORY)

ALL NEGATIVE VALUES



CENTER PLANE FLOW FIELD
UWAL 1/8 SCALE MODEL TUNNEL

SEPT. 1, 1965

3